VŠB - Technical University of Ostrava

Faculty of Electrical Engineering
and Computer Science

Department of Electronics

Modelling of Selected Structures of Electrical Controlled Drives in OrCAD/PSpice Environment

Modelování vybraných struktur elektrických regulovaných pohonů v prostředí OrCAD/PSpice

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VŠB - Technical University of Ostrava
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Bachelor Thesis Assignment

Student:	**Phuc Hau Nguyen**
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The thesis language:	English

Description:

1. Create a generic mathematical model of an electrical controlled drive with a separately excited DC motor supplied from controlled rectifier or DC/DC converter.
2. Translate the assembled model into the OrCAD / PSpice environment, perform its optimization, and allow entrering and modification of key variables using parameters.
3. Use the outputs from the implemented model to modernize the laboratory tasks from the subject Electrical Controlled Drives I.

References:

Leonhard, W.: Control of Electrical Drives. Springer-Verlag Berlin Heidelberg New York, ISBN 3-540-59380-2, 1997.
Boldea, I.-Nasar, S. A.: Electric Drives. Third Edition, CRC Press, 2016. ISBN 978-1-4987-4820-9.

Extent and terms of a thesis are specified in directions for its elaboration that are opened to the public on the web sites of the faculty.

Supervisor: **Ing. Aleš Havel, Ph.D.**

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“I hereby declare that this bachelor’s thesis was written by myself. I have quoted all the references I have drawn upon.”

30th April 2019, Ostrava.

Student’s signature

Hau

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ABSTRACT

The main objective of this thesis is to model and simulate the structures of separately excited DC motors in OrCAD/PSpice environment. The speed and current are designed and controlled in DC drive supplied by the power converter. Also, the issues and solution of the controllers figured out as integral windup effect. The analysis and evaluation of the result of the simulation are mentioned. Besides, the theory about principles of DC motors and power supply for DC drives like 6 pulses controlled rectifier or DC/DC converter also is studied in this thesis work.

Keywords: Anti-windup, Current loop, Controlled rectifier, DC motor, DC/DC converter, OrCAD/PSpice, PI controller, PID controller, Speed loop.

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Abbreviations and symbols

1. Physical symbols:

Symbol	Description	Unit
B	Magnetic flux density	T
c	Machine constant	-
d	Duty cycle	-
f	Frequency	Hz
F	Force	N
I	Current	A
J	Moment of inertia	$kg \cdot m^2$
K	Gain	-
K_d	Derivative gain	-
K_i	Integral gain	-
K_p	Proportional gain	-
l	length	m
L	Inductance	H
n	Speed	rpm
P	Power	W
q	Number of pulses	-
R	Resistance	Ω
T	Torque	Nm
U	Voltage	V
U_m	Amplitude of AC supply voltage.	V
α	General angle, firing angle	°
δ	Damping	-
η	Efficiency	%
τ	Normalised time constant	s
ϕ	Magnetic flux	$V \cdot s$
ω	Angular speed	$rad.s^{-1}$

2. Abbreviations and indexes used:

a	Armature
ABM	Analog Behaviour Modelling
DC	Direct Current
E	Excitation field
i	Induced
in	input
L	Load
M	Motor
m	mechanical
n	nominal
OM	Optimal Module
out	Output
PI	Proportional-Integral
PID	Proportional-Integral-Derivative
SO	Symmetrical Optimum

Introduction

Nowadays, modern power electronics and electric drive are used widely over the mechanical industry. The power converters are used in electric motor drive. AC or DC voltage can be taken from DC supply or conventional AC supply. There are many types of power converters which have output lower or higher than input supply based on types of semiconductor components, especially it's switching. Switching plays an important role in achieving high-efficiency power conversion. In this thesis, I will focus on the structure and principle of separately excited Direct Current Motor supplied from DC/DC converter, then creating the mathematical model and designing the controllers for DC motor in OrCAD environment.

1 Overview

Electric drive is a device converts electric energy to mechanical energy which has been invented and come to be the common choice for mechanical industrial for more than century. The direct current motor was selected as the best solution to use in many heavy industrial applications. With the high starting torque, it is suitable to use a motor in load traction such as automotive traction, electric train, conveyor, turntables, elevator and the other. Compared with AC motor, DC motor has a lower cost. Efficiency up to 85% to 90%. Besides, there is the simple and efficient design of DC motor, it has an adjustable speed which is easy to control speed by terminal voltage or potentiometer, making the service of operation and maintenance become a quicker and easier and low cost for maintenance. DC motor also can be used for braking and reversing.

1.1 Principle of DC motor

DC motor uses direct current or the direction of current flow in one direction. The motor has structure included stator (inductor, it is called stator cause its stationary part) and rotor (armature, it is called rotor because it rotates) which rotor has iron winding coil energized by commutator through brushes. The winding coil is placed among the south pole and north pole. Its operating principle base on Fleming' left-hand rule to determine the direction of the motor. This rule says that the index finger of left hand is replaced for direction of force which has to be perpendicular with the surface of the rotor, middle finger of left hand is replaced for direction of armature current, when direct current is transferred by brush through commutator, its create two force has the same magnitude, parallel and in the opposite direction, those two forces produce a torque which runs a motor. This force is based on Lorentz Force law and definition of electric current, so we have an equation:

$$F = B \cdot I \cdot l \tag{1}$$

where I is the electric current,
l is the length of wire, which is aligned which the direction of electric current,
B is the magnetic field.

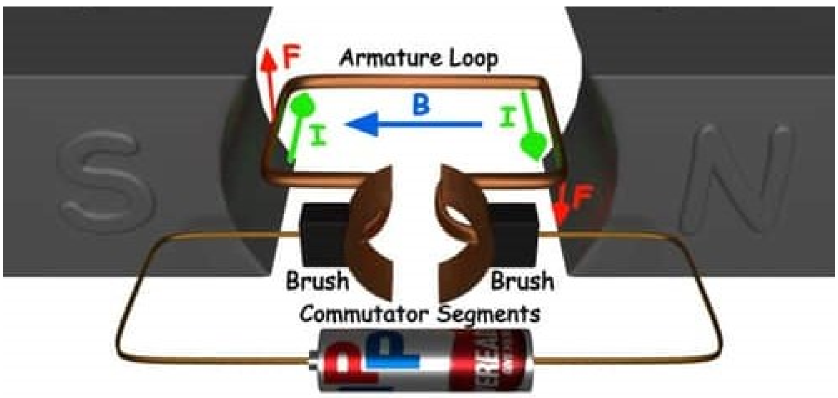


Figure 1. The simplicity of operation DC motor [1]

And because not the torque in all the positions are the same so the torque is produced by:

$$T = F \cdot cos\alpha \cdot l_1 \tag{2}$$

$$T = B \cdot I \cdot l_1 \cdot a \cdot cos\alpha \tag{3}$$

where F is force is tangential to the direction of armature rotation,
a is the length of winding coil aligned to the direction of magnetic field B when it is still perpendicular to the flow of electric current.

Maximal torque will occur when cosα = 1, but also when α = 0°. Minimal torque when cosα = 0, it is mean α = 90° so the armature winding rotates 90°from the initial position.

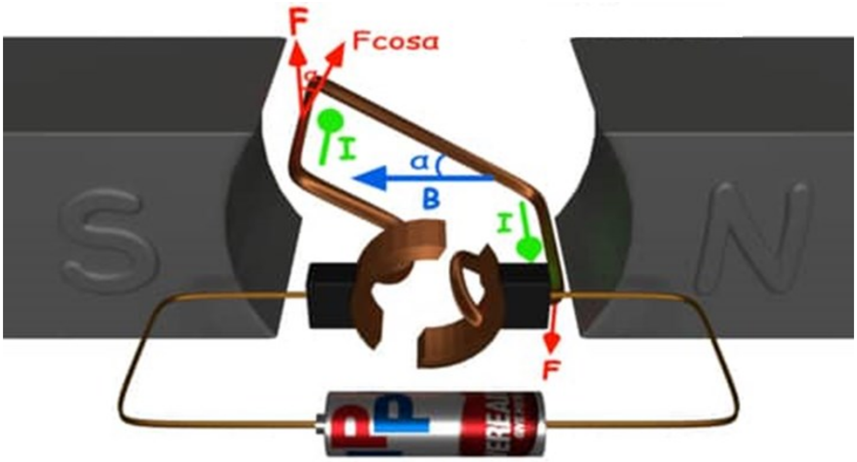


Figure 2. DC motor when coil of wire rotating. [1]

1.2 Types of DC Motors

In DC motor, there are 4 type of excitation system based on the connection of armature winding (rotor) and field excitation (stator)

- Separately exited motor: the field excitation is independent to the armature winding.

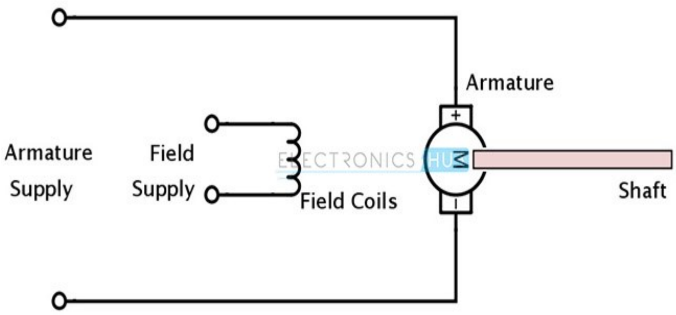


Figure 3. Separately excited motor [2]

- Shunt wound motor: the field excitation is parallel with the armature winding

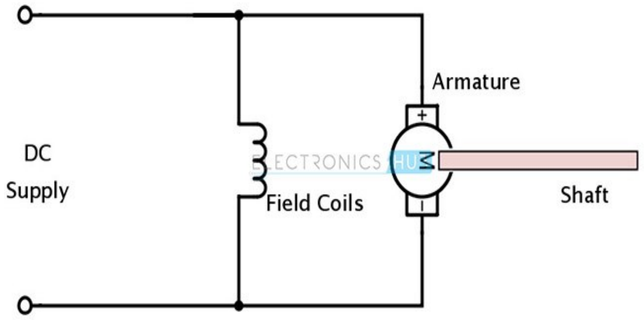


Figure 4. Shunt wound motor [2]

- Series wound motor: the field excitation is series with the armature winding. And this type of motor is used widely for electric traction because it has high torque at the beginning with low speed and low torque at high speed

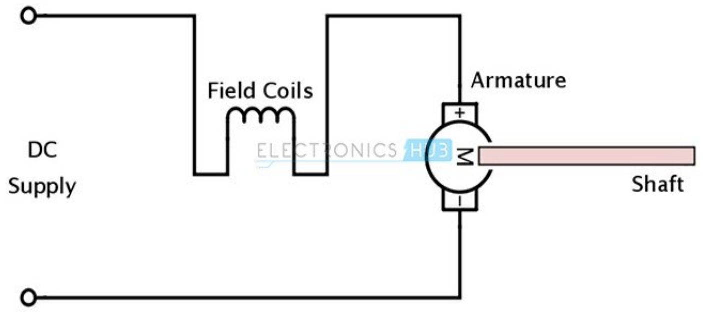


Figure 5. Series wound motor [2]

- Compound wound motor: combination of series-wound motor and shunt wound motor.

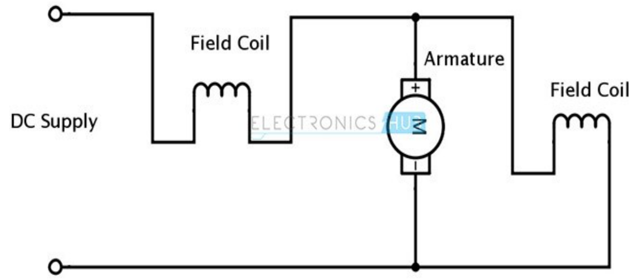


Figure 6. Compound wound motor [2]

1.3 Structure of separately excited DC motor

Separately excited DC motor has no connection between armature and field winding. Current is supplied by an independent source.

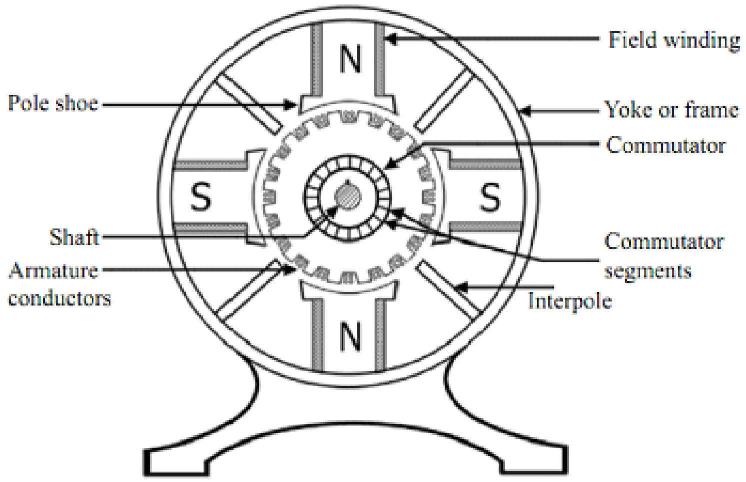


Figure 7. Structure of DC engine [3]

- **Armature:** known as a rotor, it is a moving part which turns the shaft to create mechanical power. Usually, the rotor made of steel laminate to prevent the eddy current which is the magnetic current is produced in a coil of wire and it is can induce heat up the core metal and also, it's preventing flux losses. Therefore, steel laminate is a good solution to solve core losses. Armature part is composed of segments. There is a coil of wires are designed to be fit into the armature core or segments. These coils have one head connected to commutator segments. This commutator segment works like contact point with carbon brushes so that current will go to brushes and commutator segments then through a coil of wire and make armature parts become an electromagnet.

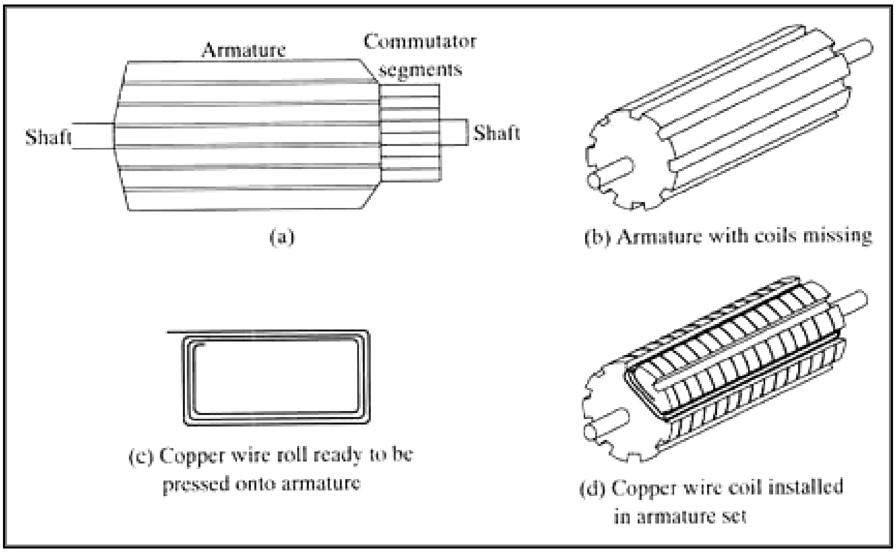


Figure 8. Parts of engine. [3]

Figure 9. Armature part. [4]

- **Field excitation:** Known as stationary, it has a permanent magnet. It generates a magnetic field which surround the rotor. Armature part is cover by Yoke or frame as in figure 5a) and inside the yoke, pole core and pole shoe as in figure 5b) are mounted rigidly on the frame, then some coil of wire is designed to be fit into the pole with default number turn of wire for specific motor. When current goes through a coil of wire, the pole will become electromagnet and it provides magnetic flux. Both yoke or pole are made of laminated steel like armature part which function is to prevent the eddy current or other flux losses.

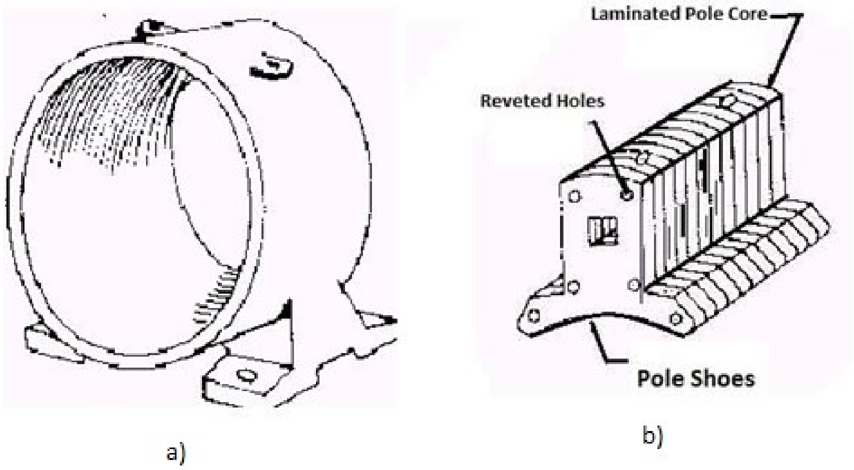


Figure 10. a) Yoke or frame. b) Pole

- **Brush and commutator:** Commutator help changes AC current to DC current and provides it to armature part. The brush creates torque to motor by supply source from commutator, stationary magnetic and rotating electromagnets. Brush usually made from carbon or graphite

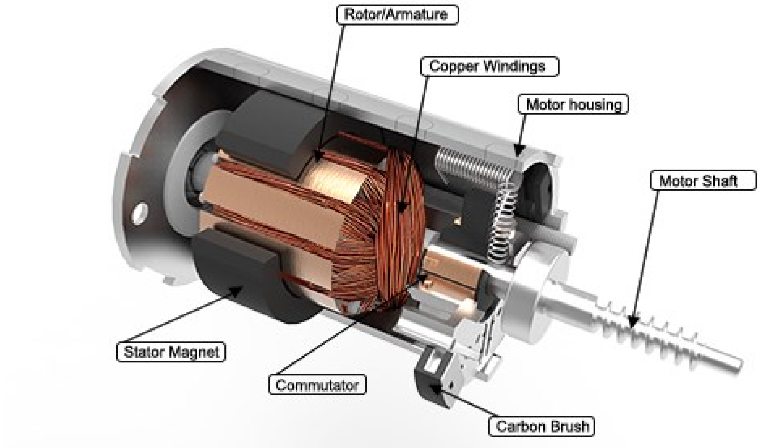


Figure 11. A cutaway picture of DC motor. [5].

1.4 Mechanical characteristic of separately excited DC motor

DC motor has the speed proportional rate with the armature voltage and inversely with the field current, however, the torque has proportional with the armature current. There are 3 methods to control the speed of separately excited DC motor and each method will decide the torque-speed characteristic of motor:

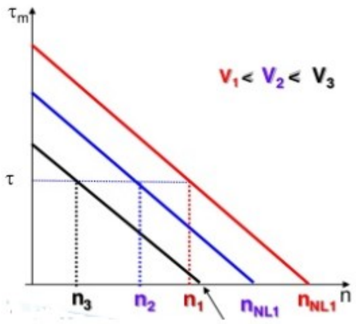


Figure 12. Armature terminal – Voltage speed control [6]

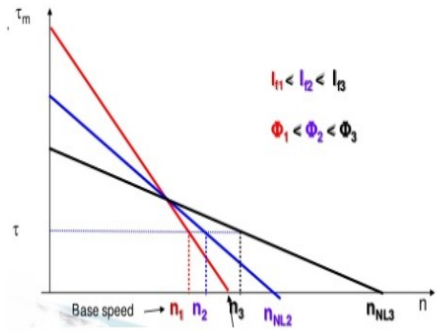


Figure 13. Field speed control [6]

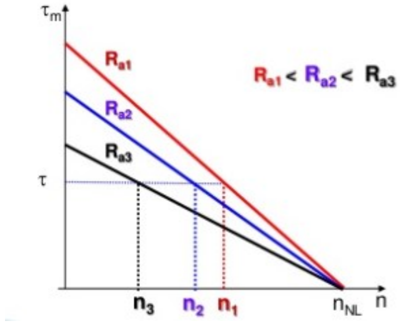


Figure 14. Armature resistance speed control [6]

1.5 Multi-quadrant operation

An electric drive can run in both ways, forward and reverse motion with braking (regenerate) in both directions even. Figure 16 shows the relation between speed and torque of electric motor which torque of forwarding and reverse motion follow the same its direction but for braking, the torque of motor run opposite to the direction of its motion..

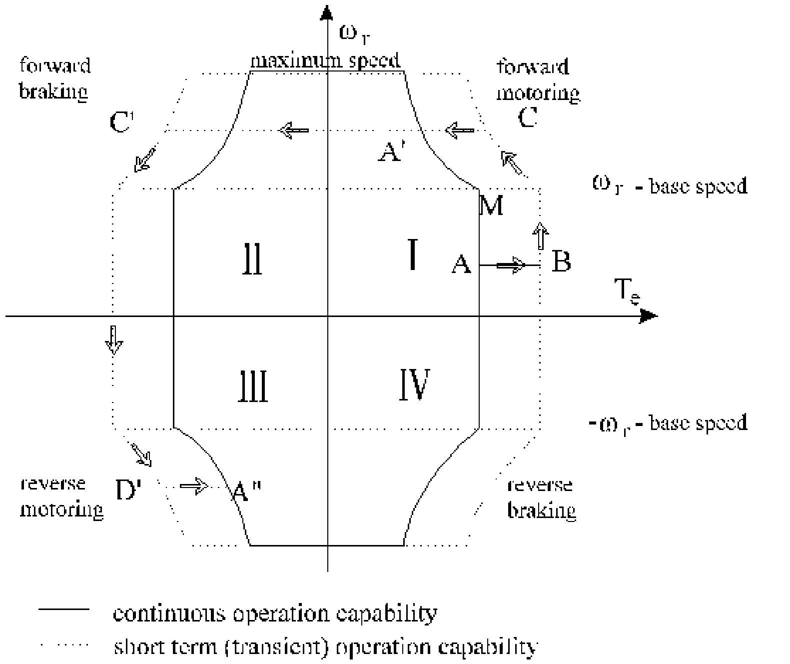


Figure 15. The torque and speed for variety of speed [7]

2 Power converters for DC motors

Power converter is an electrical device to convert energy. In this part, there will be mentioned about controlled rectifier and DC/DC converter which are two possibilities to supply power for DC drives to get the nominal speed with high starting current at the beginning. Thyristor converter refers to use in some large power application and even used in closed-loop DC motor drives to supply controlled power to the armature field

2.1 6 pulse controlled rectifier for a DC motor

For high power applications as DC motors with 15kW, 6 pulses controlled rectifier can work as a supply power. Thyristors or power transistor can be used in the converter scheme. 6 pulse controlled rectifier has 6 pulses and it occurs firing transient every period in a steady state of the motor. There firing angle plays a very important role in output average voltage, six pulses give a short interval of firing transient, so it makes control faster with a short delay. The configuration is shown on the figure. When tree phase-controlled rectifier scheme is implemented, the simplifying assumption should be considered so converter should satisfy conditions as:

- Switches have no voltage drop or leakage current.
- Instantaneous switching of thyristor which is ideal commutation, zero resistance in switch on state, infinite resistance in switch off state.
- Sinusoidal voltage source

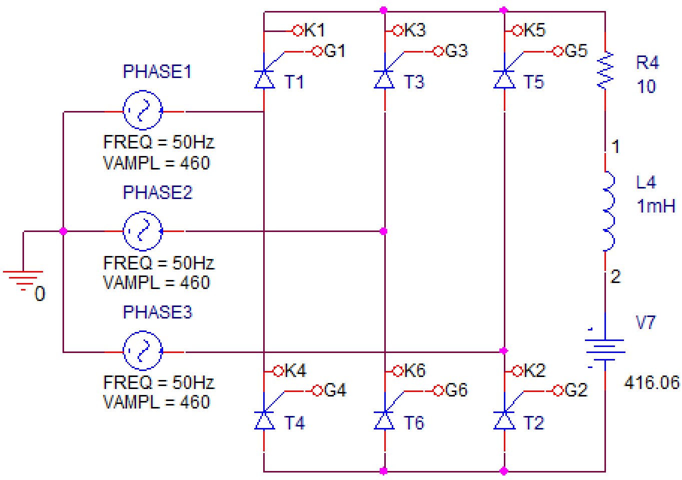


Figure 16. DC motor fed from 6 pulse controlled rectifier

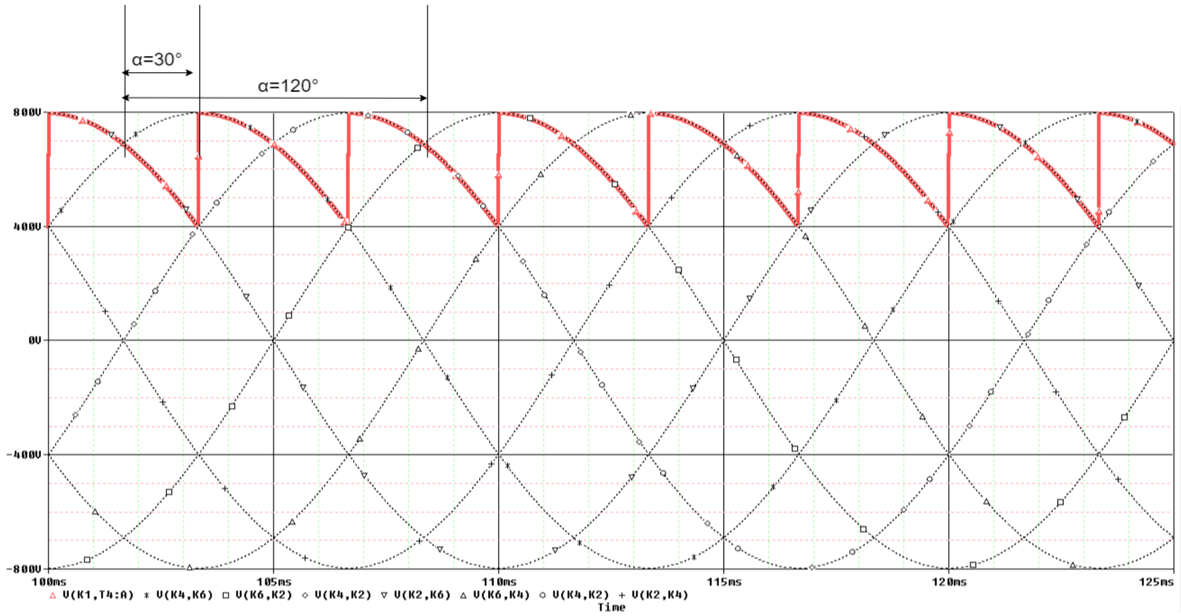


Figure 17. Output voltage fed from 6 pulse controlled rectifier with control angle α=30°

In figure 17, there is output voltage fed from 6 pulses controlled rectifier which created from 3 pair of firing angle in every period, each pair has an interval of 120°. 6 pulse rectifier converts both polarities of the input waveform to DC. Control angle α=30° is named as "natural" firing instant which α can be varying to make different output voltage. If α=0°, it's will rectifier maximum output voltage, if firing angle α is higher than 30°, the output voltage will be decreased

Transfer function include gain of thyristor K_{tr} and time constant of converter which will be used in modelling DC drives:

$$F(s) = \frac{K_{tr}}{1 + s \cdot T_{tr}} \tag{2.1}$$

T_{tr} is time constant of converter:

$$T_{tr} = \frac{1}{2 \cdot f \cdot q} \tag{2.2}$$

$U_{LAV}(0°)$ is average voltage at 0 degree, calculated by equation:

$$U_{LAV}(0°) = U_m \cdot \frac{q}{\pi} \cdot \sin(\frac{\pi}{q}) \tag{2.3}$$

There firing angle play very important role in output average voltage or armature voltage it follows equation:

$$U_{LAV} = U_{LAV}(0°) \cdot \cos\alpha \tag{2.4}$$

2.2 4 Quadrant DC/DC converter for DC motor

The DC-DC converter is an electronic circuit designed to convert DC voltage into a desired level of voltage. A separately excited DC motor is fed from a four-quadrant chopper. Four quadrant operation is good at fast response reversible. There two types of continuous current and discontinuous current but continuous current gives more energy than discontinuous current for high power application. This converter uses the same principle and involves the use of inductors, capacitors, diode and a switching circuit. The same as converter above, the DC/DC converter should consider the condition as:

Ideal power supply:

- zero impedance of the power supply

Ideal semiconductor components with:

- zero resistance in switch on state
- infinite resistance in switch off state
- instantaneous switching (switching on, switching off) of transistor ≡ ideal commutation

Output average voltage level depend on duty cycle or time when transistor turn on, approaching equation is displayed as:

$$U_{LAV} = U_{IN} \cdot \frac{t_{on}}{T} = U_{IN} \cdot d \tag{2.5}$$

Where U_{LAV} is output average voltage, U_{IN} is input voltage, t_{on} is time when transistor turn on, T is period, d is duty cycle.

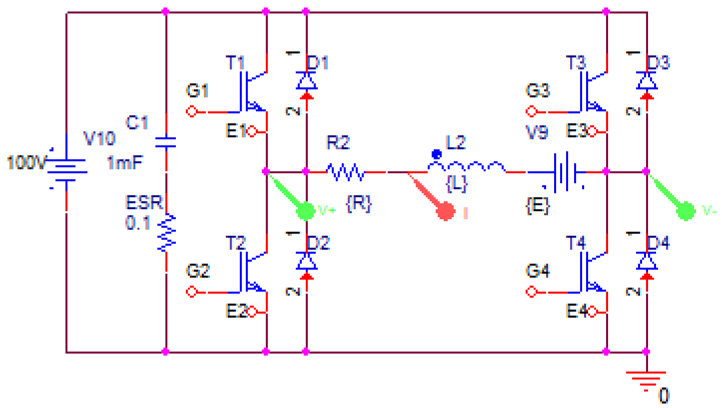


Figure 18. DC motor fed from 4 quadrant DC/DC converter.

2.2.1 Bipolar control

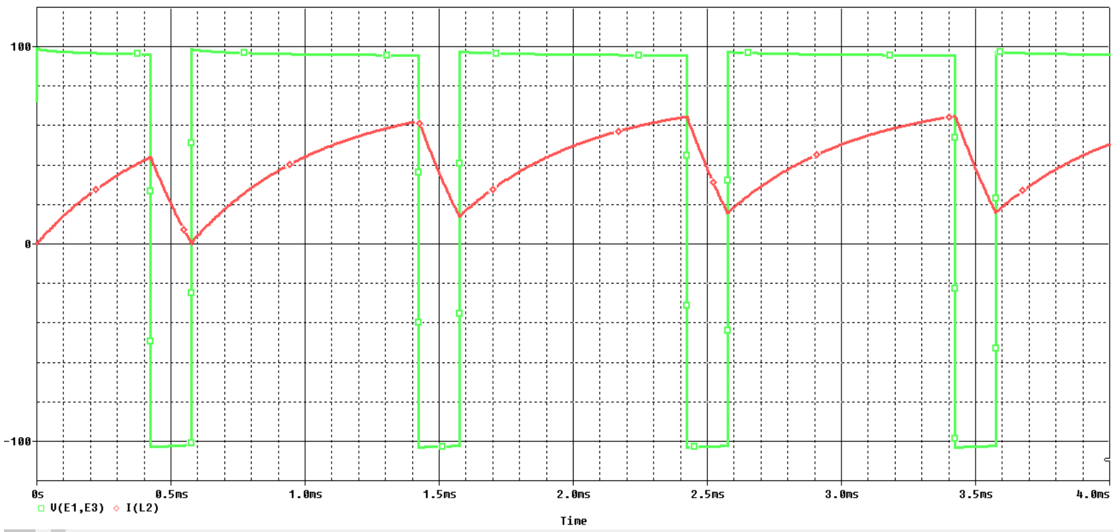


Figure 19. Output waveform of voltage and current with $I_a>0$, $-100<U_a<100$

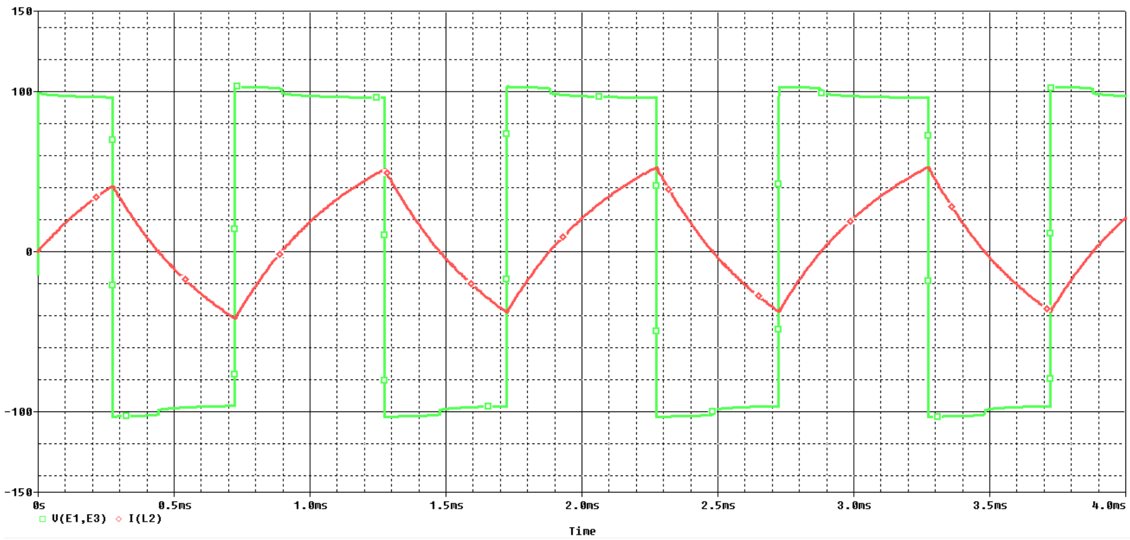


Figure 20. Output waveform of voltage and current with $-40<I_a<40$, $-100<U_a<100$

Bipolar uses two control semiconductor switches and two diodes which is turning in pairs. As we see, in bipolar, the output voltage flows in both side positive and negative. Current in figure 19 flows in only in the positive side but figure 20 current flows both side positive and negative.

2.2.2 Unipolar control

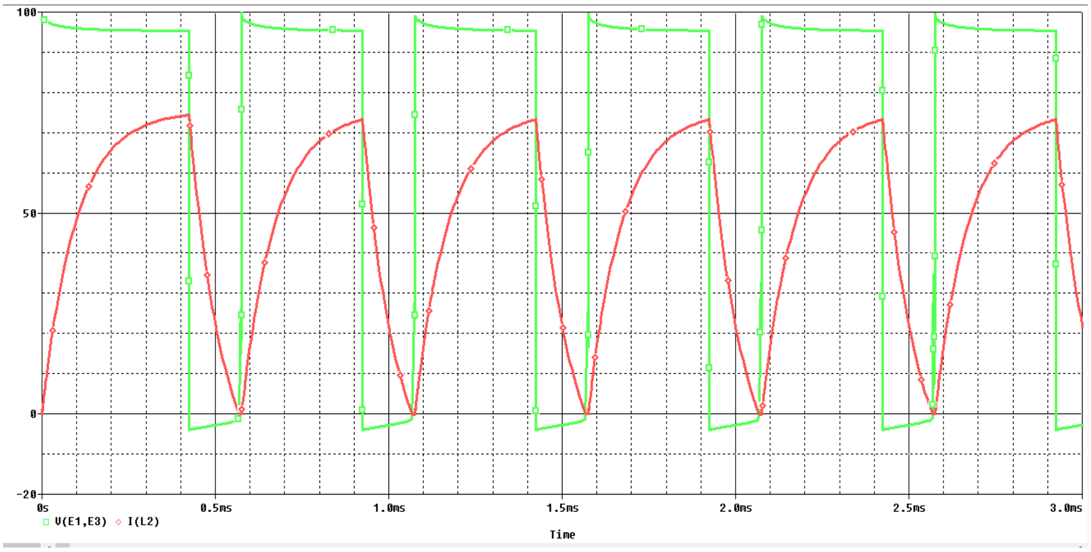


Figure 21. Output waveform of voltage and current with 0<I_a<75, 0<U_a<95

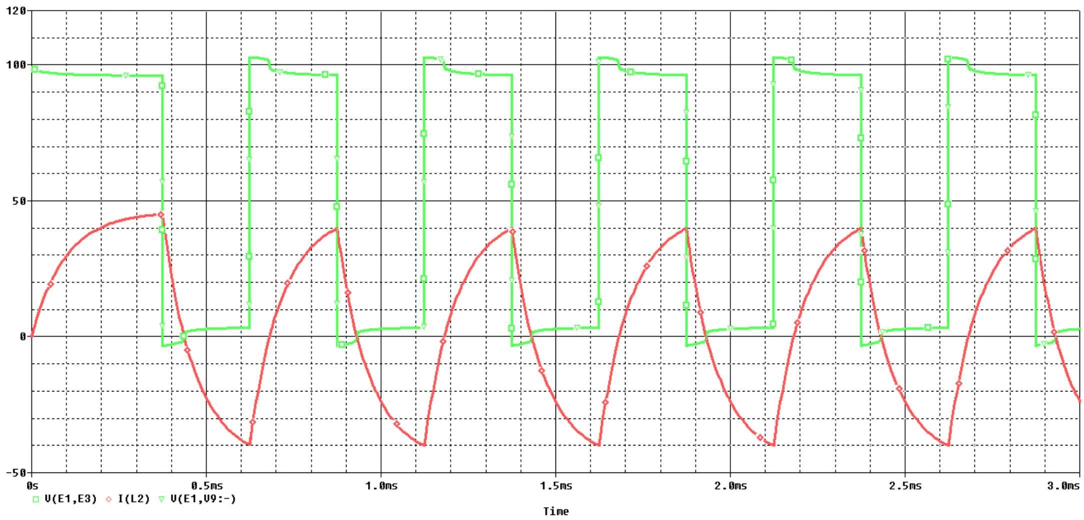


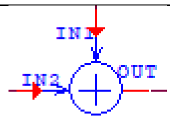
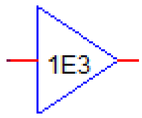
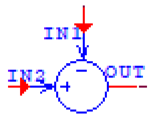
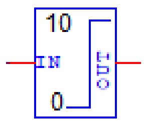
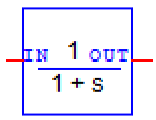
Figure 22. Output waveform of voltage and current with -40<I_a<40, 0<U_a<100

In unipolar, output voltage only flows in the positive side, figure 21 current flows only in the positive side but figure 22, current flows in both side positive and negative

3 Modelling DC motor in OrCAD/PSpice environment

3.1 Short introduction to ABM library

PSpice is a software that supports to draw analog circuit and model the behaviour of the circuit, the engineer can design and test before manufacturing any circuit board or IC. This short page is purposed to describe analog behaviour modeling (ABM), specific about functionality fundamental of a block which will be used in simulation DC motor in this chapter. In table control system parts, which groups category by function, detail description and properties, a symbol of parts. The simulation of DC motor is implemented by PSpice version 16.6.

Part	Description	Symbol
	Basic component	
SUM	Work as Adder which has 2 input and 1 output, the output is the sum of two input voltage.	
GAIN	Is a constant gain value, provides 1 input and 1 output. This part multiplied the input by the constant gain which can be given by gain property then the output is the result.	
DIFF	Evaluate the voltage difference between two inputs, the result shows on output provides 1 input and 1 output,	
	Limiter	
LIMIT	Restricts the output by a specific range which can be given in limit property. This specific range included HI and LO which: HI is upper limit value and LO is a lower limit value	
	Laplace transform	
LAPLACE	LAPLACE part is determining the output for each value input which includes 1 input and 1 output. Laplace has properties NUM and DOM which: NUM is the numerator of Laplace expression	

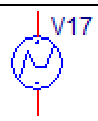
	DOM is denominator of Laplace expression. The input of LAPLACE part is voltage	
	Source	
VPWL	Pulse source has properties of time (T1…T8) and voltage (V1…V8)	

Table 1. Control system parts [8]

3.2 Examples of PI controller design with ABM blocks

Example 1: Design a PI controller with parameters: gains $K_1 = 40$, $K_2 = 0.1$, $K_3 = 1$, $K_4 = 0.15$, time constants $T_1 = 3$ms, $T_2 = 10$ms, $T_3 = 80$ms, $T_4 = 2$ms

a) Define the type
b) Define gain and time constant of controller by both method OM and SO.

Calculations:

Time constant:
$$\tau_\sigma = \tau_1 + \tau_2 + \tau_4 = 3 + 10 + 2 = \underline{\underline{15ms}} \quad (3.1)$$

Gain:
$$K = K_1 \cdot K_2 \cdot K_3 \cdot K_4 = 40 \cdot 0.1 \cdot 1 \cdot 0.15 = \underline{\underline{0.6}} \quad (3.2)$$

System:
$$F_{s(p)} = F_{1(p)} + F_{2(p)} + F_{3(p)} + F_{4(p)} \quad (3.3)$$

PI transfer function:
$$\frac{K_1}{1 + p \cdot \tau_1} \quad (3.4)$$

System with PI controller:

$$F_s(\mathrm{p}) = \frac{K_1}{1 + p \cdot \tau_1} \cdot \frac{K_2}{1 + p \cdot \tau_2} \cdot \frac{K_3}{1 + p \cdot \tau_3} \cdot \frac{K_4}{1 + p \cdot \tau_4} = \frac{K_1 \cdot K_2 \cdot K_3 \cdot K_4}{(1 + p \cdot \tau_3) \cdot (1 + p \cdot \tau_\sigma)} \quad (3.5)$$

+ Using OM method:

$$F_{C(OM)} = \frac{F_{OM}}{F_s(\mathrm{p})} = \frac{\dfrac{1}{2 \cdot p \cdot \tau_\sigma \cdot (1 + p \cdot \tau_\sigma)}}{\dfrac{K}{(1 + p \cdot \tau_3) \cdot (1 + p \cdot \tau_\sigma)}} = \frac{1 + p \cdot \tau_3}{2 \cdot p \cdot \tau_\sigma \cdot K} = \underbrace{\frac{\tau_3}{2 \cdot \tau_\sigma \cdot K}}_{K_C} \cdot \underbrace{\frac{1 + p \cdot \tau_3}{p \cdot \tau_3}}_{PI-type} \quad (3.6)$$

From result, PI type can be seen from here with gain K_c:

$$K_C = \frac{\tau_3}{2 \cdot \tau_\sigma \cdot K} = \frac{80}{2 \cdot 15 \cdot 10^{-3} \cdot 0.6} = \underline{\underline{4.44}}$$
$$\tau_C = \tau_3 = \underline{\underline{80ms}} \quad (3.7)$$

+ Using SO method:

$$F_{C(SO)} = \frac{F_{SO}}{F_s(\mathrm{p})} = \frac{\dfrac{1+4\cdot p\cdot\tau_\sigma}{8\cdot p^2\cdot\tau_\sigma{}^2\cdot(1+p\cdot\tau_\sigma)}}{\dfrac{K}{(1+p\cdot\tau_3)\cdot(1+p\cdot\tau_\gamma)}} = \frac{(1+p\cdot\tau_3)\cdot(1+4\cdot p\cdot\tau_\sigma)}{8\cdot p^2\cdot\tau_\sigma{}^2\cdot K} \tag{3.8}$$

where: $1 + p \cdot \tau_3 \approx p \cdot \tau_3$

so

$$\rightarrow \frac{p\cdot\tau_3\cdot(1+4\cdot p\cdot\tau_\sigma)}{8\cdot p^2\cdot\tau_\sigma{}^2\cdot K} = \underbrace{\frac{\tau_3}{\quad}}_{K_C}\cdot\underbrace{\frac{1+p\cdot\tau_\sigma}{\quad}}_{PI-type} \tag{3.9}$$

$$\tau_C = 4\cdot\tau_\sigma = 4\cdot 15ms = \underline{\underline{60ms}}$$

From calculations, we have $K_C = 4.4$, τ_C (OM)= 80ms, τ_C (SO)=60ms

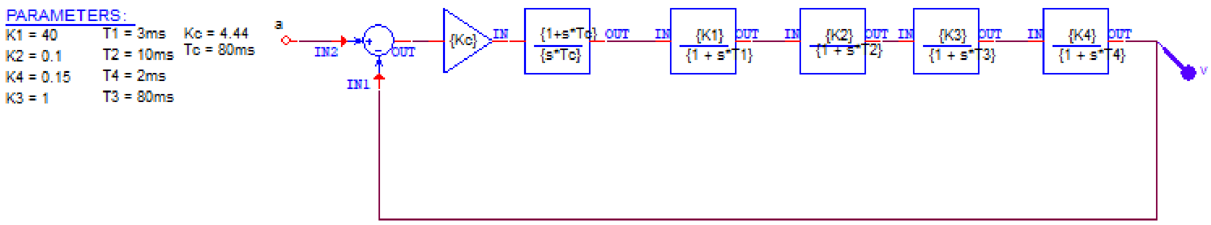


Figure 23. Close loop of PI controller connects to system.

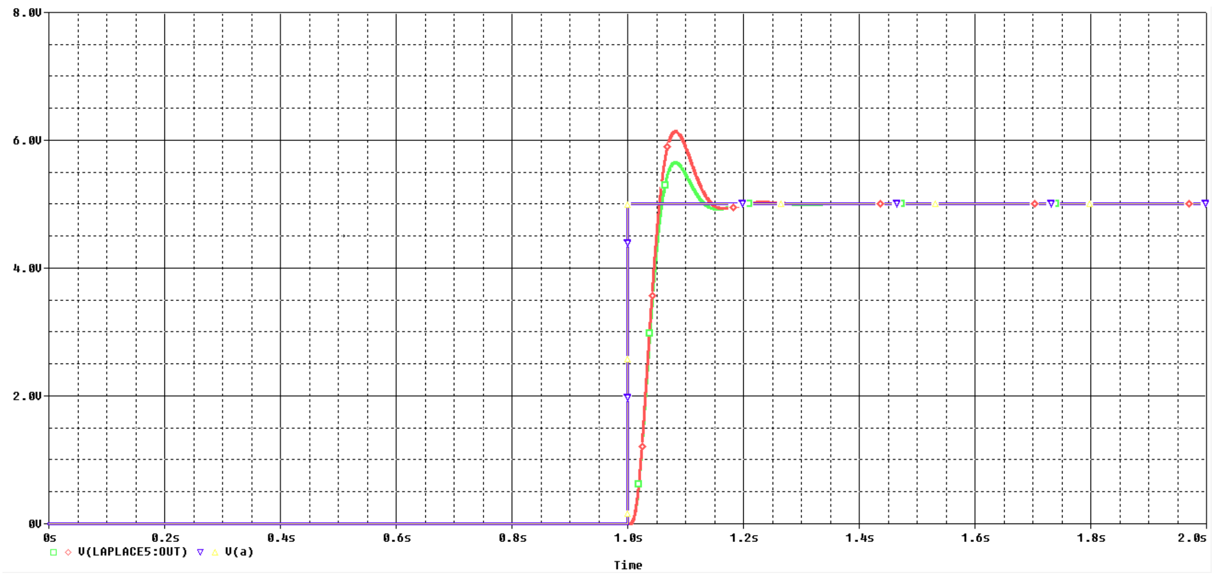


Figure 24. Output with set point (blue), OM (green) and SO (red) method

As seen in figure above, smaller value of time constant of PI controller create bigger overshoot. For SO method we have 25% overshoot while for OM method we have 15% overshoot.

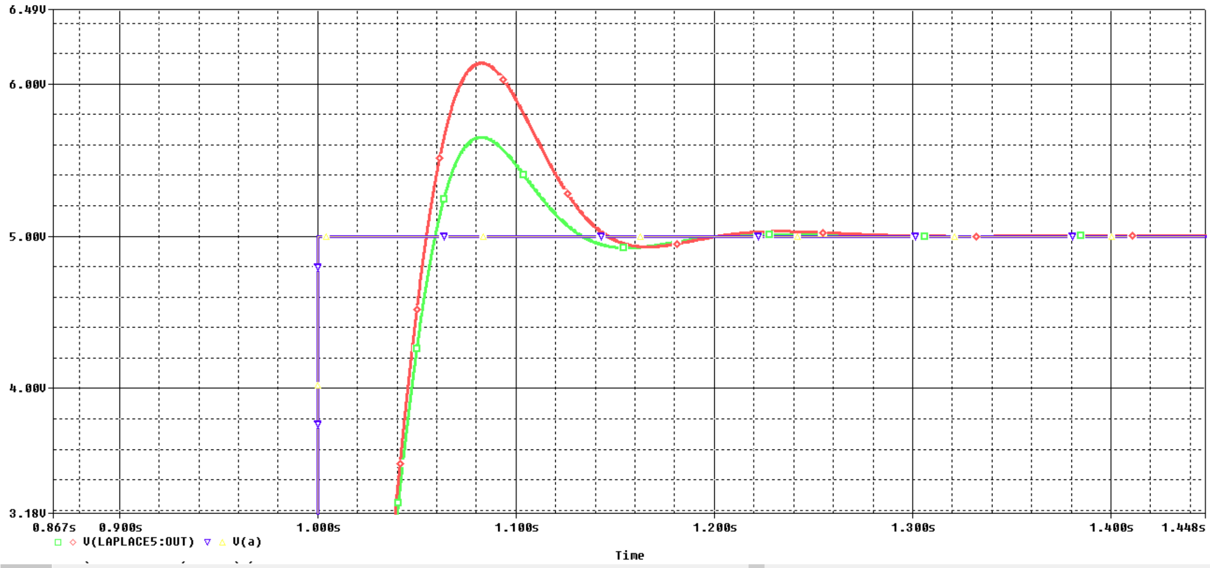


Figure 25. Detail of the overshoot

Example 2: Design a PI controller for the system below with overshoot 15% in the step response

$$F_{1(p)} = \frac{1}{1+p\cdot\tau_1}\,;\quad F_{2(p)} = \frac{1}{1+p\cdot\tau_2}$$

Time constant τ_1=0.1; τ_2=0.02

Calculations:

Transfer function of system:

$$F_{s(p)} = F_{1(p)}\cdot F_{2(p)} = \frac{1}{1+p\cdot\tau_1}\cdot\frac{1}{1+p\cdot\tau_2} = \frac{1}{(1+p\cdot\tau_1)\cdot(1+p\cdot\tau_2)} \tag{3.10}$$

Transfer function of PI controller:

$$F_{PI(p)} = K_C\cdot\frac{1+p\cdot\tau_C}{p\cdot\tau_C} \tag{3.11}$$

We have open loop:

$$F_{OL(\mathrm{p})} = F_{s(p)}\cdot F_{PI(p)} = K_C\cdot\frac{1+p\cdot\tau_C}{p\cdot\tau_C}\cdot\frac{1}{(1+p\cdot\tau_1)\cdot(1+p\cdot\tau_2)} \tag{3.12}$$

Set $\tau_C = \tau_1$

So $$F_{OL(\mathrm{p})} = \frac{K_C}{p \cdot \tau_1 \cdot (1 + p \cdot \tau_2)} \tag{3.13}$$

Close loop: $$F_{CL(\mathrm{p})} = \frac{F_{OL(\mathrm{p})}}{1 + F_{OL(\mathrm{s})}} \tag{3.14}$$

Substitute transfer function of (3.13) to (3.14):

$$F_{CL(\mathrm{p})} = \frac{\dfrac{K_C}{p \cdot \tau_1 \cdot (1 + p \cdot \tau_2)}}{1 + \dfrac{K_C}{p \cdot \tau_1 \cdot (1 + p \cdot \tau_2)}} = \frac{K_C}{K_C + p \cdot \tau_1 + p^2 \cdot \tau_1 \cdot \tau_2} = \frac{1}{1 + p \cdot \dfrac{\tau_1}{K_C} + p^2 \cdot \dfrac{\tau_1 \cdot \tau_2}{K_C}} \tag{3.15}$$

We have second order system: $$F_{(p)} = \frac{K}{1 + 2 \cdot p \cdot \delta \cdot \tau + p^2 \cdot \tau^2} \tag{3.16}$$

1) $$2 \cdot \delta \cdot \tau = \frac{\tau_1}{K_C} \rightarrow \tau = \frac{\tau_1}{2 \cdot \delta \cdot K_C} \tag{3.17}$$

2) $$\tau^2 = \frac{\tau_1 \cdot \tau_2}{K_C} \tag{3.18}$$

$$\rightarrow \frac{{\tau_1}^2}{4 \cdot \delta^2 \cdot {K_C}^2} = \frac{\tau_1 \cdot \tau_2}{K_C} \rightarrow K_C = \frac{\tau_1}{4 \cdot \delta^2 \cdot {K_C}^2} \tag{3.19}$$

We have equation of overshoot:

$$\sigma = e^{-\pi \cdot \sqrt{\frac{\delta^2}{1-\delta^2}}} \rightarrow \ln \sigma = -\pi \cdot \sqrt{\frac{\delta^2}{1-\delta^2}} \tag{3.20}$$

$$\rightarrow \ln^2 \sigma = \pi^2 \cdot \frac{\delta^2}{1-\delta^2} \rightarrow \ln^2 \sigma \cdot (1 - \delta^2) = \pi^2 \cdot \delta^2 \tag{3.21}$$

$$\rightarrow \ln^2 \sigma - \delta^2 \cdot \ln^2 \sigma = \pi^2 \cdot \delta^2 \rightarrow \delta^2 = \frac{\ln^2 \sigma}{\ln^2 \sigma + \pi^2} = \underline{\underline{0.2672}} \tag{3.22}$$

Substitute δ^2 to (3.19) we have:

$$K_C = \frac{\tau_1}{4 \cdot \delta^2 \cdot {K_C}^2} = \underline{\underline{4.678}} \tag{3.23}$$

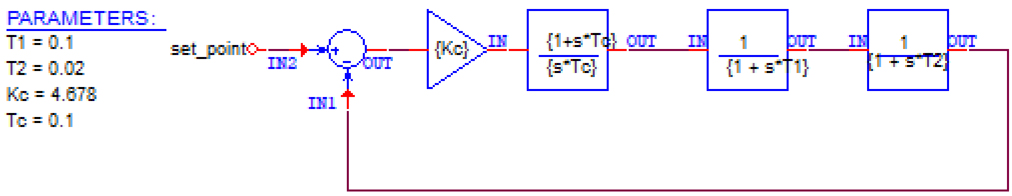


Figure 26. Close loop of PI controller with system.

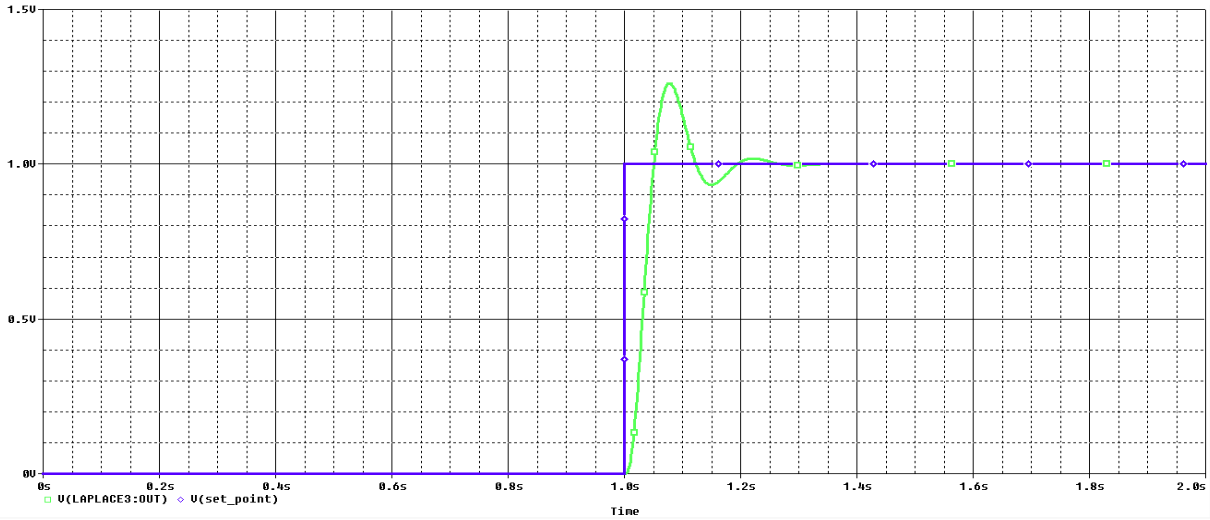


Figure 27. Output of close loop with overshoot 15%

3.3 Equivalent circuit and basic equations of DC motor

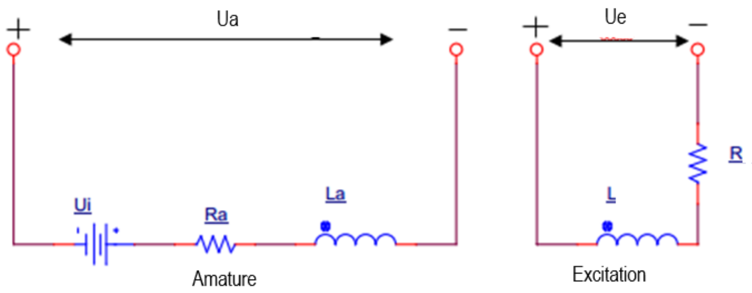


Figure 28. Equivalent diagram of DC machine

Apply the Kirchhoff Voltage Law (KVL) to equivalent circuit lead to equation (4) for armature voltage and torque equation:

$$U_a = U_i + R_a I_a + L_a \frac{di_a}{dt} \tag{3.24}$$

In steady state, time derivative is zero, so the equation of Armature voltage is displayed:

$$U_a = U_i + R_{a.} I_a \tag{3.25}$$

Induced voltage:

$$U_i = c\varphi \cdot \omega \tag{3.26}$$

Substitute equation (3.25) to (3.26), we have:

$$U_a = c\varphi.\omega + R_{a.} I_a \tag{3.27}$$

Angular speed:

$$\omega = \frac{U_a}{c\varphi} - \frac{R_{a.} I_a}{c\varphi} \tag{3.28}$$

And torque of motor:

$$T_M = c\varphi \cdot I_a \tag{3.29}$$

Armature current:

$$I_a = \frac{T_M}{c\varphi} \tag{3.30}$$

From (3.30), substitute to (3.28) we have angular speed:

$$\omega = \frac{U_a}{c\varphi} - \frac{R_{a.} \cdot T_M}{c\varphi^2} \tag{3.31}$$

Because U_a, R_a and flux are constant, so speed will depend on torque $\omega = f(T)$

Power of motor:

$$P_M = T_M . \omega_M \tag{3.32}$$

We have equation:

$$T_M - T_L = J \frac{d\omega}{dt} \tag{3.33}$$

Electrical time constant or so-called armature time constant:

$$\tau_a = \frac{L_a}{R_a} \tag{3.34}$$

Mechanical time constant:

$$\tau_m = \frac{J \cdot R_a}{(c\varphi)^2} \tag{3.35}$$

Efficiency of motor:

$$\eta = \frac{P_{out}}{P_{in}} \cdot 100\% \tag{3.36}$$

3.4 Parameters of simulated DC drive

Parameters of DC motor		
Nominal output power	P_n	15 kW
Nominal armature voltage	V_{an}	440 V
Nominal armature current	I_{an}	37.5 A
Total moment of inertia	J_{tot}	0.27 kg.m2
Armature inductance	L_a	15 mH
Parameters of thyristor rectifier		
Gain	K_{TR}	54
Time constant	τ_{TR}	1.67ms
Parameters of current sensor		
Gain	K_I	0.33
Time constant	τ_I	1ms
Parameters of speed sensor		
Gain	K_{TG}	0.095
Time constant	τ_{TG}	1ms

Table 2. Parameter of the electrical controlled drive in the lab E103

Calculations approach based on basic equations and parameter of DC motor in table 2 which is given in subject Electrical controlled drive I:

Armature time constant:

$$\tau_a = \frac{L_{an}}{R_{an}} = \frac{15 \cdot 10^{-3}}{0.64} = \underline{\underline{23.4mH}} \tag{3.37}$$

Mechanical time constant:

$$\tau_m = \frac{J \cdot R_a}{(c\varphi)^2} = \frac{0.64 \cdot 0.27}{(1.42)^2} = \underline{\underline{85.7ms}} \tag{3.38}$$

Armature gain:

$$K_a = \frac{1}{R_{an}} = \frac{1}{0.64} = \underline{\underline{1.56}} \tag{3.39}$$

Nominal magnetic flux of motor:

$$c\phi = U_{an} - \frac{R_{an} \cdot I_{an}}{\omega_n} = 440 - \frac{0.64 \cdot 37.5}{293} = \underline{\underline{1.42Vs}} \tag{3.40}$$

Nominal angular speed of motor:

$$\omega_n = \frac{2 \cdot \pi \cdot n_n}{60} = \frac{2 \cdot \pi \cdot 2800}{60} = \underline{\underline{293rad.s^{-1}}} \tag{3.41}$$

Nominal torque of motor: $$T_m = \frac{P_n}{\omega_n} = \frac{15000}{293} = \underline{\underline{51.2Nm}} \tag{3.42}$$

Efficiency of motor:

$$\eta = \frac{P_{out}}{P_{in}} \cdot 100\% = \frac{15000}{37.5 \cdot 440} \cdot 100\% = \underline{\underline{90.91\%}} \tag{3.43}$$

Resistance of motor:

$$R_a(20°) = \frac{1}{2} \cdot \frac{U_{an}}{I_{an}} \cdot (1 - \frac{P_n}{U_{an} \cdot I_{an}}) = \frac{1}{2} \cdot \frac{440}{37.5} \cdot (1 - \frac{15000}{440 \cdot 37.5}) = \underline{\underline{0.53\Omega}} \tag{3.44}$$

Nominal resistance of motor:

$$\mathrm{R}_{an} = R_a(20°) \cdot 1.2 = \underline{\underline{0.64\Omega}} \tag{3.45}$$

Time constant of 6 pulse converter:

$$T_{tr} = \frac{1}{2 \cdot f \cdot q} = \frac{1}{2 \cdot 50 \cdot 6} = \underline{\underline{1.67ms}} \tag{3.46}$$

Speed of motor in rotation:

$$\omega = \frac{2\pi \cdot n}{60} \Rightarrow n = \frac{30 \cdot \omega}{\pi} = \frac{30 \cdot 293}{\pi} \approx \underline{\underline{2800rpm}} \tag{3.47}$$

3.5 Mathematical model of simulated DC drive

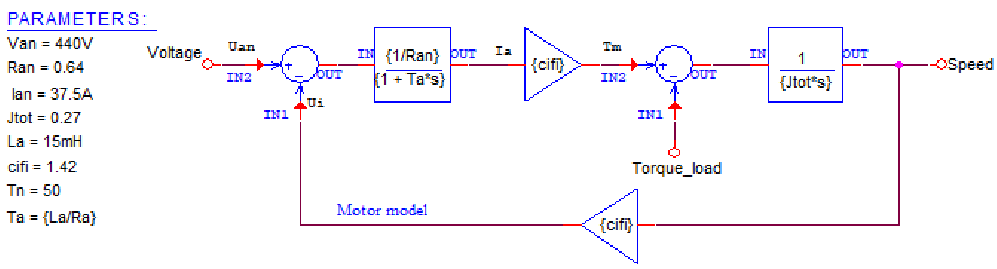


Figure 29. Parameters and model of DC motor.

In figure 30 is the model of DC motor simulated by PSpice environment and this scheme included DIFF, LAPLACE, GAIN of ABM block. This closed-loop feedback contains an electrical part, mechanical part of DC motors which fed by set voltage 440V without the controller. The transfer function of separately excited DC motor follow Laplace form

$$F_{MOT}(s) = \frac{\frac{1}{c\varphi}}{(1 + s \cdot \tau_m + s^2 \cdot \tau_m \cdot \tau_a)} \quad (3.48)$$

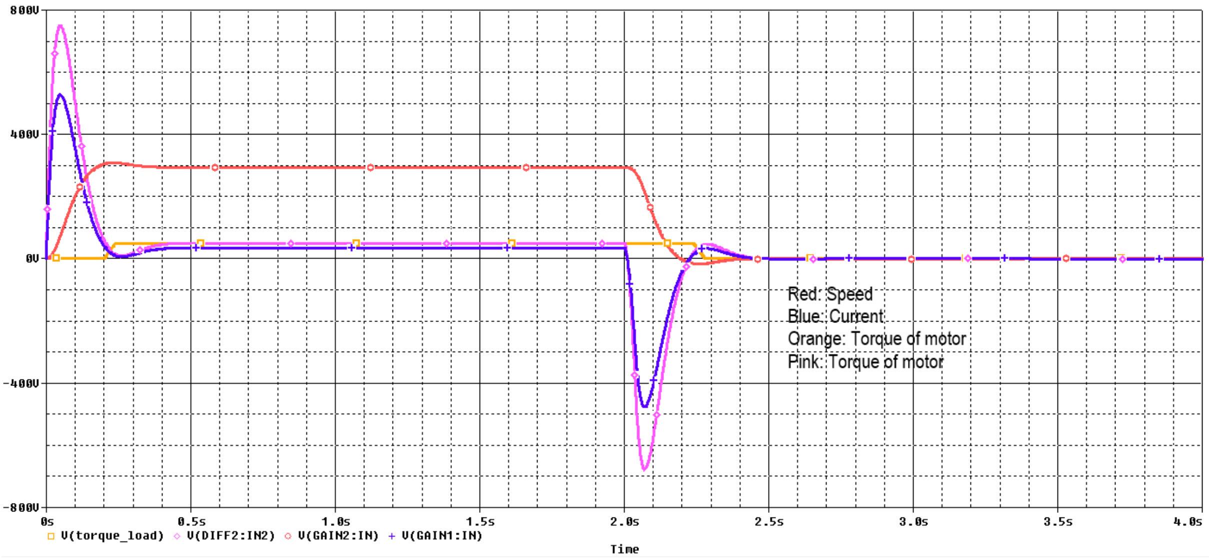


Figure 30. Output speed and current of model DC motor without controller

As we have seen in figure 30 when the motor starts to run, speed achieved it desire speed after 0.2s, maintain till 1s then the load is applied to 2s, speed drop and it get undesired speed. Starting current getting too high at the beginning without controlling of first 0.2s then when motor run in steady state, armature current is constant, when motor braking, current drop down to the negative side.

When motor accelerates torque of the motor is higher than the torque of load, but in steady state, motor torque and load torque have to match to each other or the same to get the desired speed or stable transient when motor de-accelerate toque of motor lower than the torque of load. The motion equation of DC motors is:

$$T_M - T_L = J\frac{d\omega}{dt} \quad (3.49)$$

Where T_M is torque of motor, T_L is torque of load, J is inertia

4 Close loop control of DC drives

This chapter will show the practical control problem of DC drives. Integrator windup is taken into account when the controller stand-alone then the solution will be given by adding extra process for the integral term. By modelling and simulation, these issues will be showed and analysed clearly.

4.1 General current loop of DC motor

Recently, PI (proportional-integral) controller are wide uses in industries for controlling the speed of DC motor because it has a good price, fast response, steady state, no noise, it is used more often than PID. In figure 31, closed-loop control is modelled, and it is included mainly torque control and speed control.

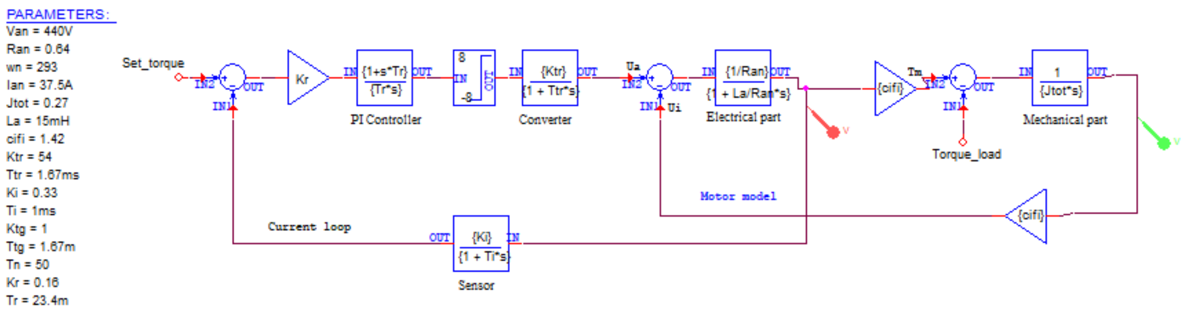


Figure 31. Parameters and model of DC motor controlled by transfer function of PI controller

In fig 31 is model includes DIFF, LAPLACE, LIMIT, and GAIN block. This model has a mathematical model of DC motors and current loop which include converter and PI controller. The transfer function of the PI controller is:

$$F_{PI}(s) = K_r \cdot \frac{1 + s \cdot \tau_r}{s \cdot \tau_r} \tag{4.1}$$

Where time constant $\tau_r = 23.4$ms and gain constant $K_r = 0.16$ have calculated by method OM from results of subject ECD 1. Current will be represented by a current sensor which connected from electrical part to input 1

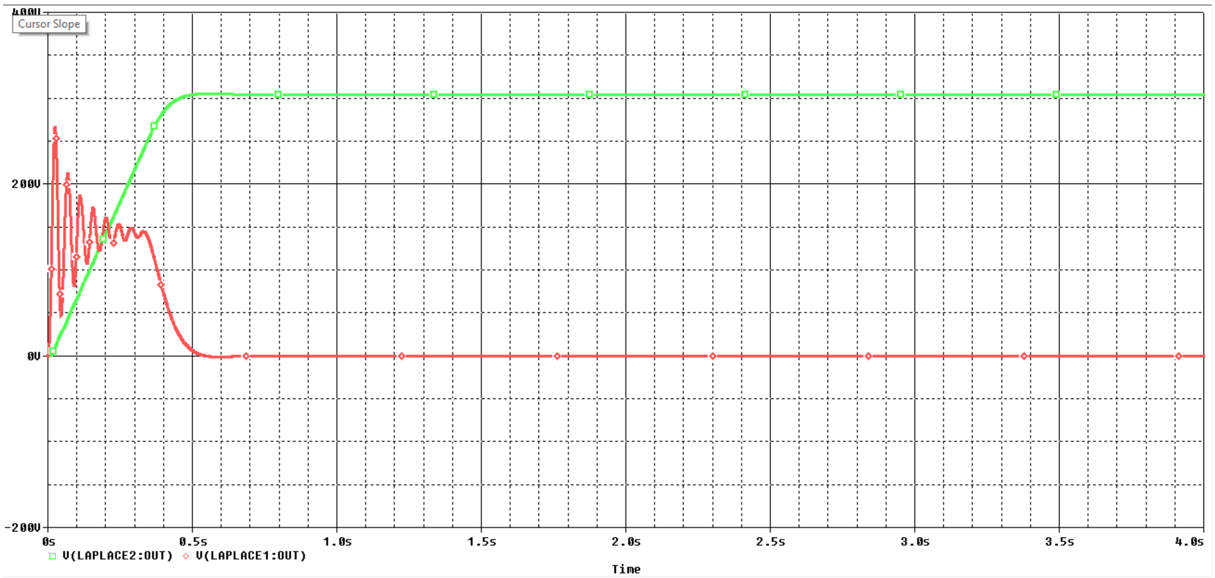


Figure 32. Output of speed and current waveform without anti-windup

In Figure 32, the green signal is actual speed and red is armature current. As we can see, starting current get overshoot and oscillates before it drops down, this is because of the integral term in controller very large and it needs to adjust and limit the current, Figure 33 is model of DC motor controlled by PI controller with anti-windup which included torque (current) loop and speed loop.

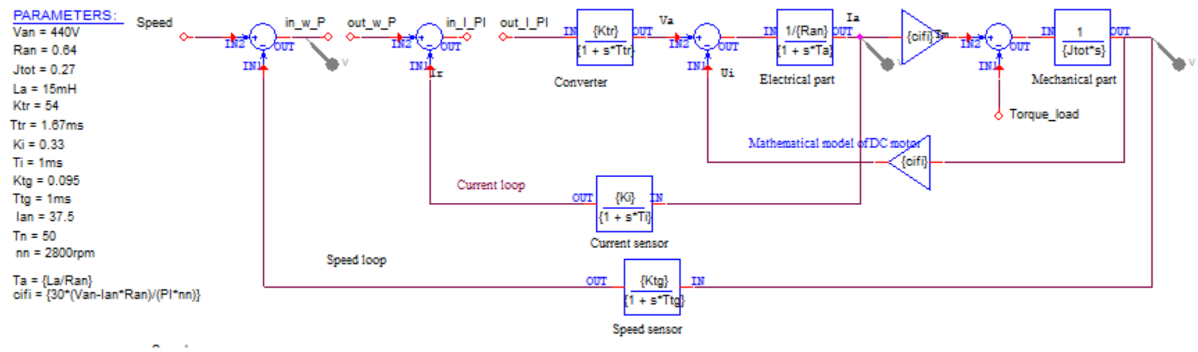


Figure 33. Parameters and model of DC motor controlled by PI controller with anti-windup

4.1.1 Current loop with limitation of PI controller

Transfer function of PI controller is expressed in Laplace transform as:

$$F_{PI}(s) = K_p + \frac{K_I}{s} \tag{4.2}$$

Where K_p is proportional gain, K_I is integral gain which $K_I = \frac{1}{\tau_r}$, K_{anti} is gain of anti-windup which is should be very high value. Proportional improve the rises time but does not improve steady state, otherwise, integral part will responsible for stability and steady state but its cause overshoot for the system.

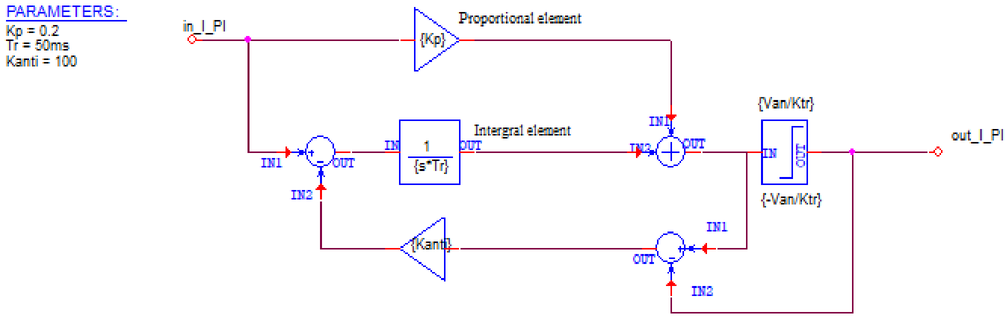


Figure 34. Scheme of current control loop with anti-windup

4.1.2 Speed loop with limitation of P controller

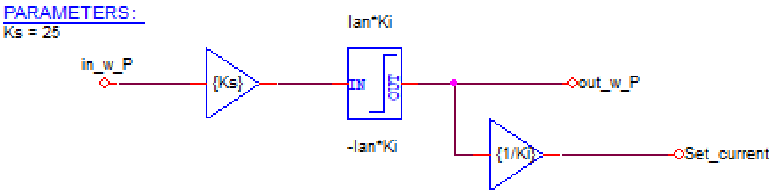


Figure 35. Scheme of speed loop with limiter

Figure 34 is scheme of speed loop which is contain only *P* type and limiter. K_s is gain constant of speed controller

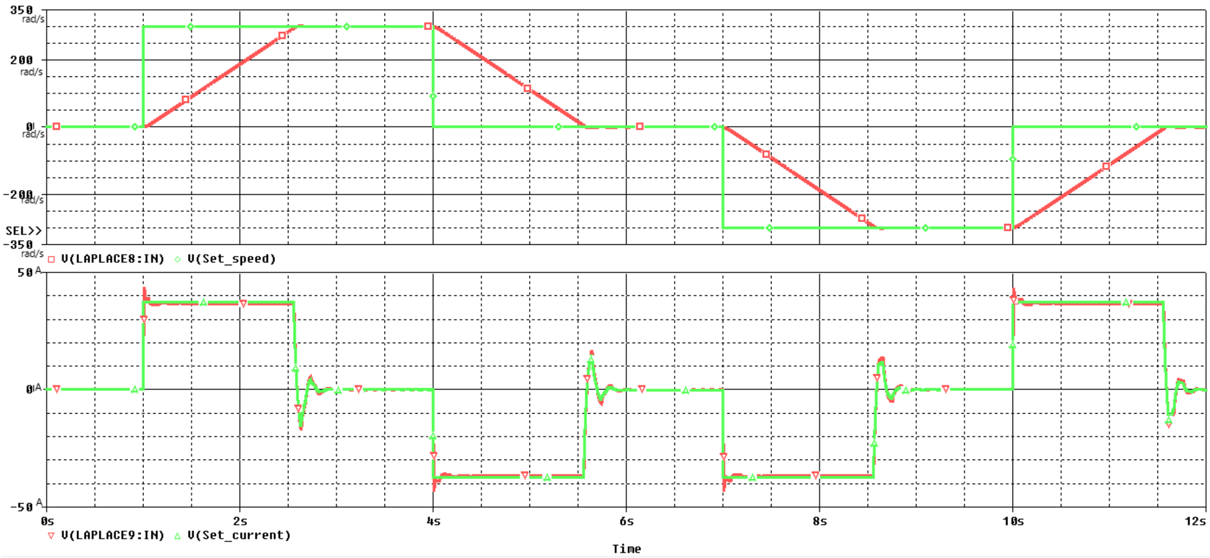


Figure 36. Output of speed and current controlled by PI controller without load

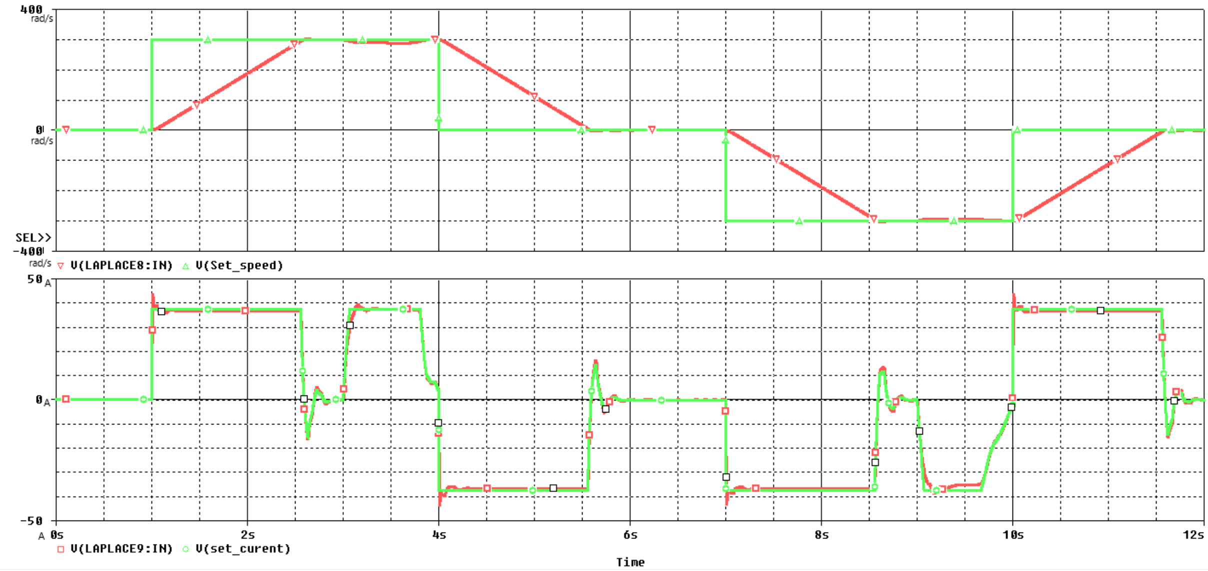


Figure 37. Output of speed and current controlled by PI controller with load is 50Nm (3s to 4s)

Fig 36 and 37 show the desired (green) and actual (red) speed of the system, which is represented above trace, desire (green) and actual (red) current of the system which is represented below trace with and without load. Both figures depict that current loop runs faster than speed loop, a current achieves it desired current immediately without ramping and remain till speed achieve desired value then current drop. In Figure 37, the speed has rising time from 1s to 2.5s to achieve the desired speed, it's settled then the load is applied from 3s to 4s. At the means time, current rise up again because of load, the speed decreasing but it gets back to the desired speed immediately because of PI controller and motor can run with forward and reverse direction.

4.2 Speed control without a current loop

PID controller is short term for proportional-integral-derivative, was used widely in the industrial control system. PID principle works the same as PI controller but the derivative element was added for correcting the error between desired input and output of closed loop for controlling DC motor, moreover, it improves overshoot. PID controller has general transfer function in the Laplace domain:

$$L(\mathrm{s}) = \mathrm{K}_P + \frac{K_I}{s} + K_d \cdot s = \frac{Kd^2 + K_P \cdot s + K_I}{s} \tag{4.4}$$

Where K_P is proportional gain, K_I is integral gain and K_d is derivative gain

Transfer function for PID controller:

$$F_{PID}(\mathrm{s}) = \mathrm{K} \cdot \frac{(1+s\cdot\tau_1)\cdot(1+s\cdot\tau_2)}{s\cdot\tau_1} \quad \text{with } \tau_1 \rangle \tau_2 \tag{4.5}$$

4.2.1 Impact of P, I and D controllers

Proportional controller improves the rise time, it means that if we are increasing the controller gain, the rise time reducing. The integral controller has an effect of eliminating the steady-state error so if we raise the controller, the system more stable but It's can cause worse transient. The derivative part makes a better transient response when it is rising. The table below gets a better understanding about working of each P, I and D elements.

Parameter	**Rise time**	**Overshoot**	**Settling time**	**Steady-state error**
K_P	Decrease	Increase	Small change	Decrease
K_I	Decrease	Increase	Increase	Eliminate
K_D	Small change	Decrease	Decrease	Small change

Table 3. Effect of increasing parameter P, I and D

Figure 38 is loop of the model of DC motor controlled by PID with only one speed loop and its a sensor. And this speed loop doesn't contain anti-windup

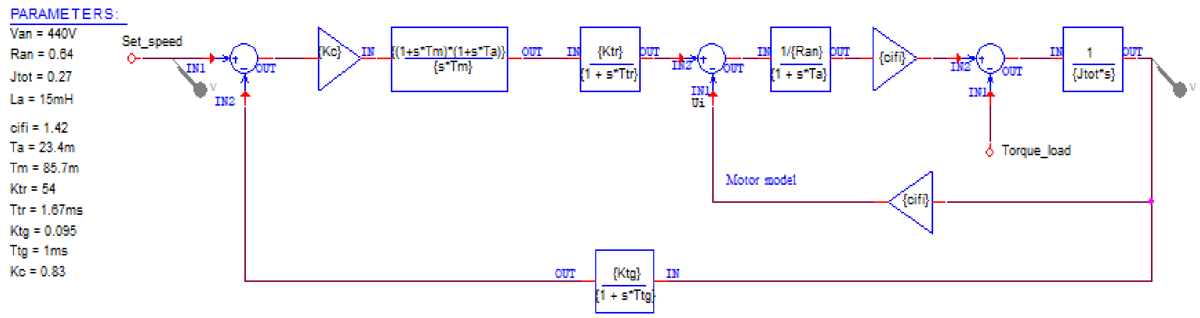


Figure 38. Scheme of DC motor controlled by the PID transfer function

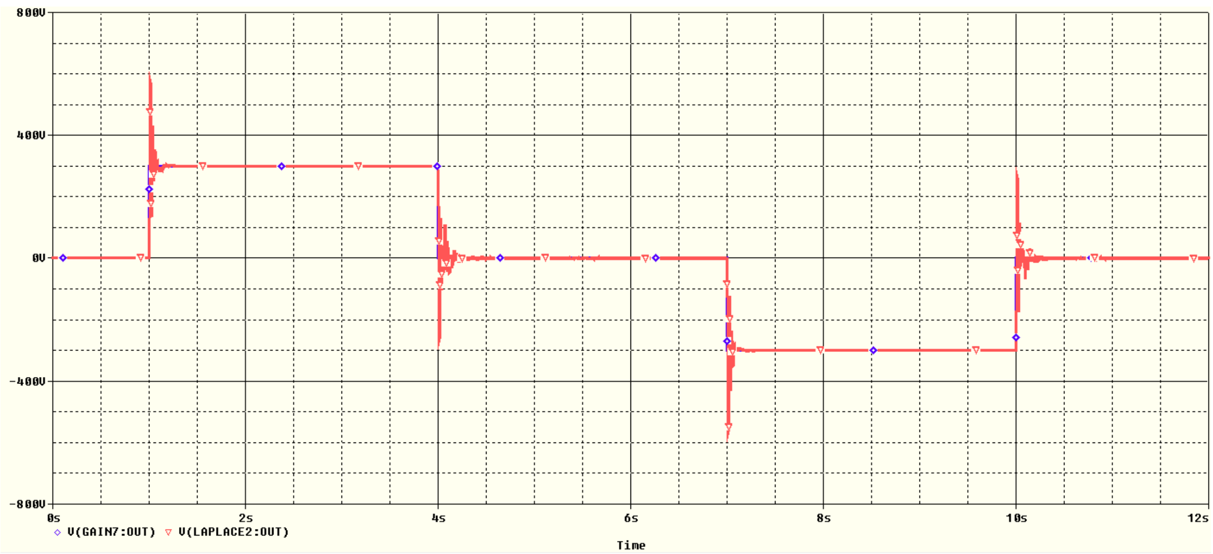


Figure 39. Output of speed controlled by PID without anti-windup

Without anti-windup, speed do not control well, badly oscillate, not stable because the P controller is too high in system as it shows in figure 39.

4.2.2 Speed loop with limitation of PID controller

Figure 40 is speed loop the same as above, but speed loop will be replaced by anti-windup scheme.

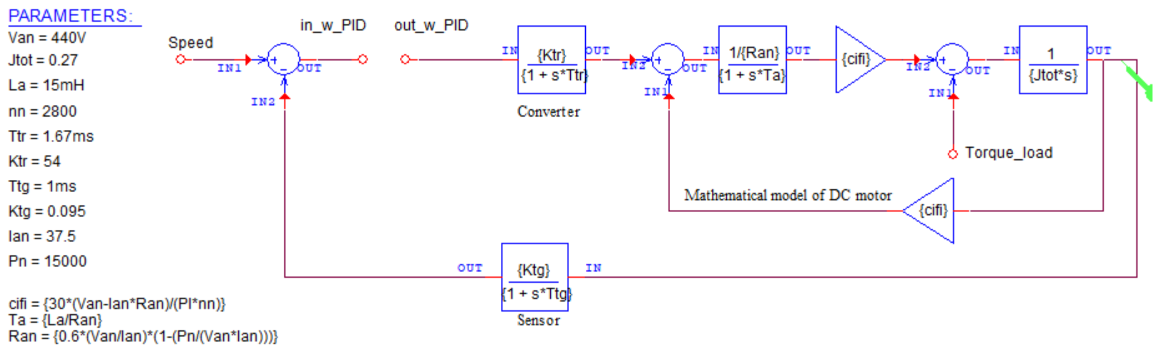


Figure 40. Parameters and model of DC motor controlled by PID controller with anti-windup

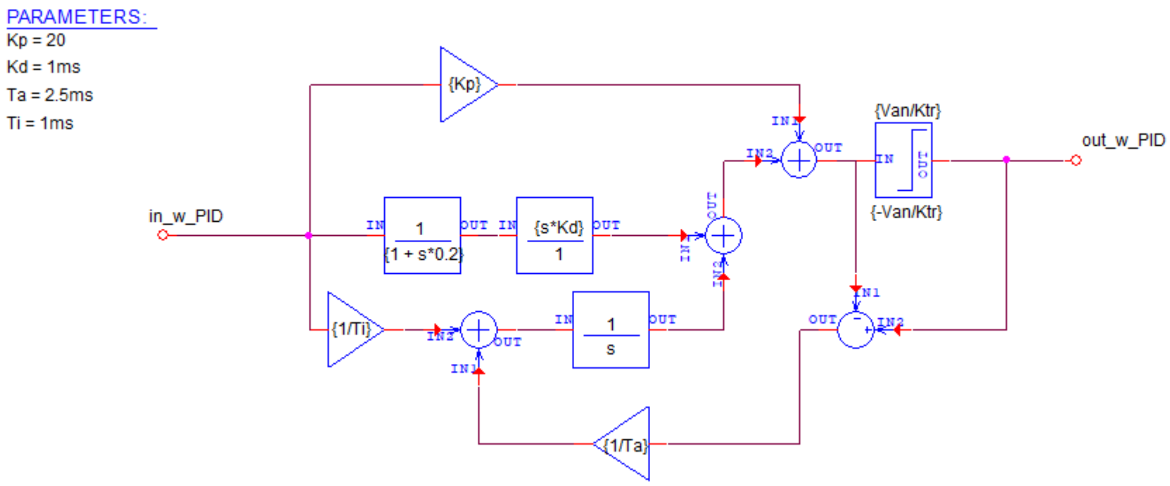


Figure 41. Anti-windup of PID controller

For removing high-frequency noise in derivative elements, low pass filter connects in series to cancel the noise. After sum of total 3 elements, there is limiter which has it output minus for sum of 3 elements multiplied for a gain of anti-windup $\frac{1}{\tau_a}$ then it value go to input 1 of SUM block on integral elements branch.

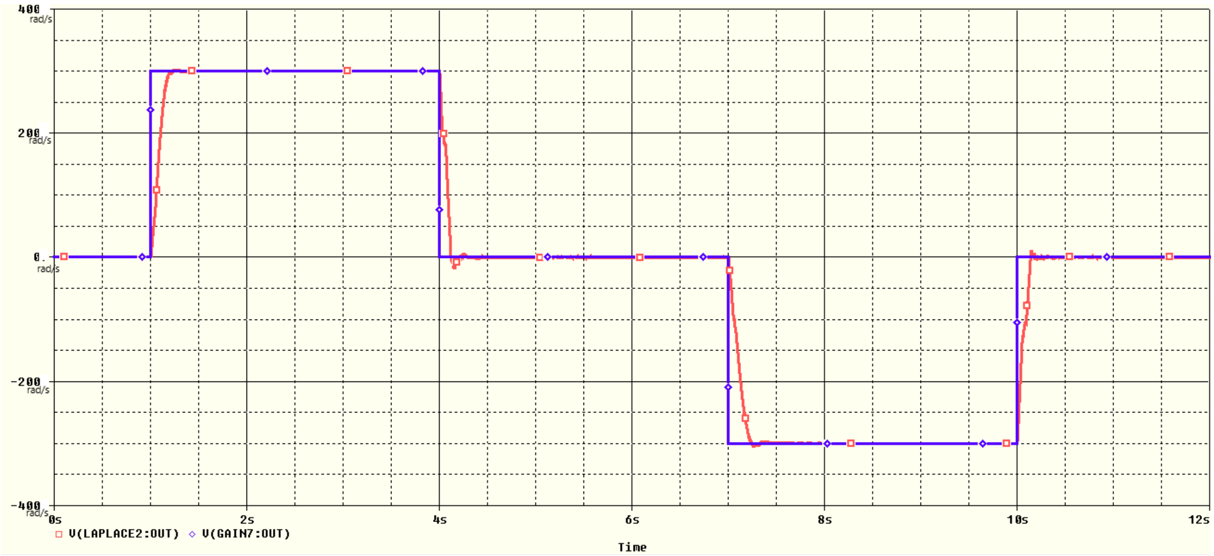


Figure 42. Output of speed using PID controller without load

Figure 42 shows waveform of speed rising from 1s to 1.2s then it's maintained the desired speed till 4s moreover, motor can run forward and reversely without problem

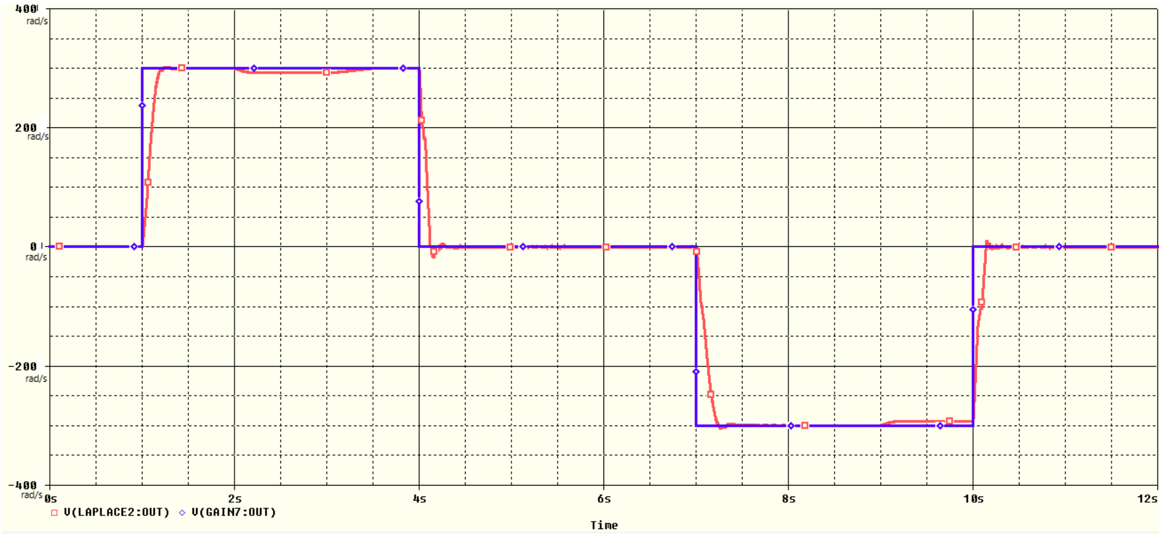


Figure 43. Output of speed using PID controller with load is 50Nm (from 2s to 3s)

Figure 43 shows speed rise from 1s to 1.2s then it's maintained till 2s, the load is applied from 2s to 3s, speed drops but then it's gotten back with desired speed, and motor can run with forwarding and reversely direction. It's doesn't have noise at all, quick transient response, steady state error is eliminated and stable.

Type	**Rise time**	**Overshoot**	**Settling time**
PI ($K_P = 0.2$, $K_I = 20$)	1.5s	0%	0.1s
PID ($K_P = 20$, $K_I = 1.42$, $K_D = 0.7$)	0.2s	0%	0.2s

Table 4. Optimal behaviour of PI and PID controller

4.3 Discussion of results

Firstly, as we can see, DC motors can run in both directions (forward and reverse) for both controllers. Secondly, the controller keeps the desired speed of the motor from dropping off when the load (error) is applied. Thirdly, with PI controller, there is included the current loop and the speed loop where current loop runs faster than the speed loop. PID controller has only one speed loop to control. The results of the simulation above show that PI and PID controller with limitation work well with or without load. One of the important elements to achieve desired speed is tuning control parameters - proportional, integral and derivation part, each of it has their own functionality and independence. From table 4, it shows that both controllers keep the system away from overshoot, with quick settling time and stable. However, the PID controller has the rise time (1.5s) much faster than the PI controller (0.2s) and better performance of the transient state.

Conclusion

This thesis studied the theory about basic structure and principles of DC motors, types of DC motors, multi-quadrant operations and power converters including 6 pulse controlled rectifiers and 4 quadrant DC/DC converters. Short introduction about ABM library in the OrCAD/PSpice is mentioned.

In the practical part, DC drive has been implemented on the PSpice/OrCAD models with parameters taken from laboratory E103's test rig. The results have been analysed and evaluated. Comparison of the P, PI and PID speed controllers with or without current loop had been made including the anti-windup solution.

In real life situations, the actuators usually are not ideal and have a maximum output limit. However, after reaching maximum output value while not reaching the desired value, the integrating part of the controller continues to work even that more power cannot be delivered by the actuator. After that, when the desired value is changed to the lower level, the integrating part has to be decreased before the actuator output value starts decreasing also, creating an unwanted delay.

As a solution, we add the actuator model (limiter) after the controller and use the difference of controller output and actuator model as a feedback loop through the gain which should be high enough, to the integrating part of the controller. You can see the scheme in Figure 34 for the PI controller and figure 41 for the PID controller.

Difference between P and PI controller in the speed loop is that only with proportional gain. There could be a steady state error which can be removed by integrating part. The integrating part increases the overshoot, settling time and decrease the rise time. The effects of the controller's parameters are shown in table 3.

The current loop is the way how to enchant the control loop by limiting the armature current so we can use bigger gain while not burning the engine which means that we need the anti-windup solution explained above. Otherwise, if we use only speed loop, the gain has to be lower or the armature current will rise without control. The disadvantage is the nonlinear behaviour.

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